Is Cosmic Acceleration Really Recent?[*]

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Abstract

In the standard cosmological paradigm cosmic acceleration is to only be a very recent (viz. $z \leq 1$) phenomenon, with the universe being required to be decelerating at all higher redshifts. We suggest that this particular expectation of the standard model is to be viewed as a quite definitive test not only of the model itself but also of the fine-tuning assumption on which the expectation is based, with the expectation itself actually being readily amenable to testing once the Hubble plot can be extended out to only $z = 2$ or so. Moreover, such a modest extension of the Hubble plot will also provide for definitive testing of the non fine-tuned alternate conformal gravity theory, a theory in which the universe is to accelerate both above and below $z = 1$.

I. THE HUBBLE PLOT OF STANDARD COSMOLOGY

In a standard pure matter or pure radiation Friedmann cosmology the attractive nature of gravity entails the existence of an initial big bang singularity followed by a subsequent decelerating expansion. Primary evidence in general favor of such a picture is obtained from observational study of three widely separated epochs, viz. early universe nucleosynthesis, the recombination era cosmic microwave background, and the current $z \leq 1$ era (d_L, z) Hubble plot. While it had long been thought that a decelerating expansion was to occur in every epoch, data accumulated only recently [1–4] now reveal the presence of an unanticipated additional repulsive component to cosmological gravity, a component most commonly attributed to the presence of a non-vanishing cosmological constant Λ, a component whose contribution to cosmic evolution is only found to start to become of consequence at around $z = 1$ or so where its presence is then central to the elucidation of the $z \leq 1$ Hubble plot data.[1] Specifically, through use of the standard Einstein-Friedmann cosmological evolution

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[1]While the cosmic microwave background data [4] are certainly compatible with the presence of a non-vanishing Λ, in and of themselves alone they can just as readily support a universe in which Λ is absent.

equation

$$\dot{R}^2(t) + kc^2 = \dot{R}^2(t)(\Omega_M(t) + \Omega_\Lambda(t)) \tag{1}$$

[where $\Omega_M(t) = 8\pi G\rho_M(t)/3c^2 H^2(t)$ is due to ordinary $\rho_M(t) \sim 1/R^n(t)$ matter and where $\Omega_\Lambda(t) = 8\pi G\Lambda/3cH^2(t)$ is due to a cosmological constant $c\Lambda$] phenomenological data fitting has been found to yield current era values of 0.3 for $\Omega_M(t_0)$ and 0.7 for $\Omega_\Lambda(t_0)$, to thus entail that in the current era the deceleration parameter $q_0 = q(t_0) = (n/2-1)\Omega_M(t_0) - \Omega_\Lambda(t_0)$ has to take the negative value of $-1/2$, with the current era universe thus not being a decelerating one after all.

While the identifying of such specific values for $\Omega_M(t_0)$, $\Omega_\Lambda(t_0)$ and $\Omega_k(t_0) = -kc^2/\dot{R}^2(t_0) = 1 - \Omega_M(t_0) - \Omega_\Lambda(t_0)$ has enabled standard cosmology to ostensibly achieve its primary purpose, namely that of determining the matter, vacuum and curvature content of the universe, and while the obtained values even provide support for the flat $\Omega_k(t) = 0$ inflationary universe paradigm [5], the particular values obtained for these parameters are nonetheless extremely perplexing. Specifically, a priori estimates for $c\Lambda \equiv \sigma T_V^4$ would suggest for T_V a value of either a typical particle physics temperature scale of order 10^{16} degrees or so or a quantum-gravitational Planck temperature scale of order 10^{33} degrees, to thereby yield an $\Omega_\Lambda(t_0)/\Omega_M(t_0)$ ratio of order 10^{60} to 10^{120}, a ratio not only overwhelmingly larger than the requisite measured value of order one, but one which would (for an $\Omega_M(t_0)$ of order one) entail that $\Omega_k(t_0)$ would have to be of order -10^{60} and thus be nowhere near flat at all.

To get round this problem the standard paradigm thus proposes that rather than use such a fundamental physics based T_V one should instead, and despite the absence of any currently known justification, fine-tune T_V down by orders and orders of magnitude so that the value $\Omega_\Lambda(t_0) = 0.7$ would then ensue. Beyond the difficulty inherent in trying to understand how this might actually be dynamically achieved, even a successful resolution of this issue would still not actually leave cosmology totally free of fine-tuning problems, since in its turn, having a current era $\Omega_\Lambda(t_0)$ of order one creates a yet further problem for the standard model, one of then having to have an expressly fine-tuned early universe. Specifically, for an $\Omega_\Lambda(t_0)$ of order one the early universe associated with Eq. (1) would need to be one in which $\Omega_M(t = t_{PL})$ would have had to have been incredibly close to one at the Planck time $t = t_{PL}$, while $\Omega_\Lambda(t = t_{PL})$ itself would have had to have been as small as $O(10^{-120})$. The early universe thus has only a one in 10^{120} chance of ever evolving into our current universe unless some explicit dynamical mechanism could be found which would naturally fix these needed initial conditions with incredible precision. In a sense this fine-tuning problem is a new variant of the venerable flatness problem. As we recall, in the pre $\Omega_\Lambda(t_0) \neq 0$ days it was very difficult to understand why an $\Omega_M(t)$ which had been redshifting for more than 10 billion years would be anywhere near one today rather than being orders and orders of magnitude smaller, with it being inflation which then provided a natural answer to this problem. Specifically, it was shown by Guth [5] that if there were to be a period of rapid de Sitter inflation (viz. rapid acceleration) prior to the onset of the current Robertson-Walker (RW) era, then such an inflationary era would precisely lead at its end to a set of initial conditions for an ensuing RW phase in which $\Omega_M(t)$ would not merely be close to one but would in fact be identically equal to one in each and every epoch and thus not susceptible to redshifting at all. However, with the advent of a non-zero cosmological constant inflation now only fixes the sum of $\Omega_M(t)$ and $\Omega_\Lambda(t)$ to be equal to one in all epochs but does not constrain

their ratio. Currently then, standard cosmology stands waiting for the development of some sort of generalized version of early universe inflation which would naturally lead to initial RW era conditions which then would naturally fix the initial values of both $\Omega_M(t)$ and $\Omega_\Lambda(t)$ to the requisite precision. This then is the challenge to the standard cosmology posed by the new $z \leq 1$ Hubble plot data.

As regards actually fitting these Hubble plot data, we note that when viewed purely as a phenomenology (i.e. without regard to any of the above fine-tuning concerns) an $\Omega_M(t_0) = 0.3$, $\Omega_\Lambda(t_0) = 0.7$ standard model then performs extraordinarily well. Through use of type Ia supernovae as standard candles the authors of [1] and [2] were able to extend the Hubble plot of luminosity versus redshift out to redshifts close to one. To illustrate the quality of the fits which then ensue we follow [2] and fit 38 of their reported 42 data points together with 16 of the 18 earlier lower z points of [6], for a total of 54 data points with reported effective blue apparent magnitude m_i and uncertainty σ_i. (While we thus, following [2], leave out 6 questionable data points for the fitting, nonetheless, for completeness we still include them in the displayed Fig. (1).) For the fitting we calculate the apparent magnitude m of each supernova at redshift z via $m = 25 + M + 5log_{10}d_L$ (the luminosity distance d_L being in Mpc) where M is their assumed common absolute magnitude, and find for $\Omega_M(t_0) = 0.3$, $\Omega_\Lambda(t_0) = 0.7$ and $M = -19.37$ that $\chi^2 = \sum(m - m_i)^2/\sigma_i^2$ takes the value 57.74, with the fit itself being displayed as the lower curve in Fig. (1). [2] As the fitting shows, once one allows for the gravitational repulsion associated with a non-vanishing $\Omega_\Lambda(t_0)$ the standard model can nicely account for the supernovae data.

With the values of $\Omega_M(t_0) = 0.3$, $\Omega_\Lambda(t_0) = 0.7$ thus being established by the $z \leq 1$ Hubble plot data, we now note that since the matter density $\rho_M(t)$ redshifts while Λ of course does not, as we go to higher and higher redshift the $\Omega_M(t)/\Omega_\Lambda(t)$ ratio will get bigger and bigger, with the attractive matter density numerically being found to overcome the repulsive Λ contribution to the deceleration parameter at a redshift of only $z = 0.67$. In the standard model then the universe would be such that it would decelerate ($q(t) > 0$) continually in all epochs until the matter density contribution finally manages to redshift itself down to the cosmological constant contribution, something which is to occur at the incredibly late $z = 0.67$ when $q(t)$ would at long last finally change sign. Indeed, the particular timing of this change in sign is itself a reflection of the standard model early universe fine-tuning problem we discussed earlier, with initial conditions having to be such that this change over would occur precisely in our own epoch, neither earlier than it nor later. Now while it is very peculiar that such a turn around is to occur just in our own particular epoch, nonetheless, independent of one's views regarding the merits or otherwise of such an expectation, the prediction itself is actually readily amenable to testing, with just a modest increase in the range of z (say to $z = 2$ or so) in the Hubble plot being able to reveal its possible presence. Moreover, such a study would be a completely kinematic one, one totally independent of dynamical assumptions (such as those for instance required for the extraction of cosmological parameters from the cosmic microwave background) and would thus be completely clear

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[2] The very fact that the data can be fitted so well with a common M at all (and even with one of value typical of nearby supernovae) strongly suggests that type Ia supernovae are indeed good standard candles.

cut. In this sense then study of the $z > 1$ Hubble plot can provide a completely dynamics independent test of whether or not Λ really is as small as the standard model's assumed fine-tuning would require. With the $z > 1$ Hubble plot thus being the "smoking gun" for a fine-tuned Λ, we thus exhibit in Fig. (2) the standard model expectation (the lowest curve) out to $z = 5$. In and of itself then it would be extremely informative to extend the range of the Hubble plot. However, as we now show, it would be of additional interest since it would allow for a rather unequivocal comparison between standard cosmology and the recently proposed alternate conformal cosmology, a theory which is capable of fitting the very same supernovae data without any fine-tuning at all.

II. THE HUBBLE PLOT OF CONFORMAL COSMOLOGY

Given both the fine-tuning problems of the standard cosmology and the absence to date of any solution to them, it is thus of value to entertain and explore possible candidate alternate cosmologies to see if any one of them might shed some light on the issue. Now while the choice of possible alternate theories is quite vast (pure metric based theories of gravity require only a general coordinate scalar action, of which there is an infinite number containing derivatives of the Riemann tensor out to arbitrarily high order), one particular such alternative is explicitly singled out. Specifically, since it possesses a symmetry which when unbroken obliges the cosmological constant to vanish identically [7], conformal gravity (viz. gravity based on the fully covariant, locally conformal invariant Weyl action

$$I_W = -\alpha_g \int d^4 x (-g)^{1/2} C_{\lambda\mu\nu\kappa} C^{\lambda\mu\nu\kappa} \tag{2}$$

where $C^{\lambda\mu\nu\kappa}$ is the conformal Weyl tensor and where α_g is a purely dimensionless gravitational coupling constant) is immediately suggested and motivated. The cosmology associated with the conformal gravity theory was first presented in [8] where it was shown to both possess no flatness problem (to thereby release conformal cosmology from the need for the copious amounts of cosmological dark matter required of the standard model) and to have an effective cosmological Newton constant, G_{eff}, which actually turned out to be negative. Thus long in advance of the recent supernovae data it had been noted that conformal cosmology possessed a repulsive gravitational component.[3] Subsequently [9,10], the cosmology was shown to also possess no horizon problem or universe age problem. And finally, it was shown [11,12] that even after the conformal symmetry is spontaneously broken by a Λ inducing scale breaking cosmological phase transition, the theory continues to be able to keep the contribution of the induced cosmological constant to cosmic evolution under control even in the event that Λ is in fact as big as particle physics suggests, to thereby provide a completely natural solution to the cosmological constant problem without the need for any

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[3]In fact, equally in advance of the supernovae data, it had also been noted [9] that in a $\Lambda = 0$ conformal cosmology the current era q_0 would then be identically equal to zero, with a $\Lambda = 0$ conformal cosmology thus possessing a repulsion not present in a $\Lambda = 0$ standard cosmology where $q_0 = 1/2$.

fine tuning at all. In the present paper we use the results of [11,12] to show that conformal gravity not only controls the cosmological constant in principle, in practice it even provides for a completely acceptable accounting of the recent supernovae Hubble plot data as well.

Analysis of the implications of conformal cosmology is greatly facilitated by considering the generic conformal matter action

$$I_M = -\hbar \int d^4x(-g)^{1/2}[S^\mu S_\mu/2 - S^2 R^\mu{}_\mu/12 + \lambda S^4 + i\bar\psi\gamma^\mu(x)(\partial_\mu + \Gamma_\mu(x))\psi - gS\bar\psi\psi] \quad (3)$$

for massless fermions and a conformally coupled order parameter scalar field. When the scalar field breaks the conformal symmetry by acquiring a non-zero expectation value S_0, the energy-momentum tensor associated with the matter action of Eq. (3) is found (for a perfect matter fluid $T^{\mu\nu}_{kin}$ of the fermions) to take the form [12]

$$T^{\mu\nu} = T^{\mu\nu}_{kin} - \hbar S_0^2(R^{\mu\nu} - g^{\mu\nu}R^\alpha{}_\alpha/2)/6 - g^{\mu\nu}\hbar\lambda S_0^4 \quad , \quad (4)$$

with the complete solution to the scalar, fermionic and gravitational field equations of motion in a background RW geometry (viz. a geometry in which $C^{\lambda\mu\nu\kappa} = 0$) then reducing [12] to the remarkably simple equation $T^{\mu\nu} = 0$, i.e. reducing to

$$\hbar S_0^2(R^{\mu\nu} - g^{\mu\nu}R^\alpha{}_\alpha/2)/6 = T^{\mu\nu}_{kin} - g^{\mu\nu}\hbar\lambda S_0^4 \quad , \quad (5)$$

with the vanishing of $T^{\mu\nu}$ immediately fixing the zero of energy. As we thus see, the evolution equation of conformal cosmology looks identical to that of standard gravity save only that the quantity $-\hbar S_0^2/12$ has replaced the familiar $c^3/16\pi G$, so that instead of being attractive the effective cosmological $G_{eff} = -3c^3/4\pi\hbar S_0^2$ is actually negative, and instead of being fixed as the standard low energy Newtonian G, the cosmological G_{eff} is instead fixed by the altogether different scale S_0, a scale which when large enough would yield an effective cosmological G_{eff} which would then be altogether smaller than the standard Cavendish G.[4]

Given the equation of motion of Eq. (5), the ensuing conformal cosmology evolution equation is then found (on setting $\Lambda = \hbar\lambda S_0^4$) to take a form remarkably similar to that of Eq. (1), viz.

$$\dot R^2(t) + kc^2 = \dot R^2(t)(\bar\Omega_M(t) + \bar\Omega_\Lambda(t)) \quad (6)$$

where $\bar\Omega_M(t) = 8\pi G_{eff}\rho_M(t)/3c^2H^2(t)$, $\bar\Omega_\Lambda(t) = 8\pi G_{eff}\Lambda/3cH^2(t)$. Further, unlike the situation in the standard theory where preferred values for the relevant evolution parameters (such as the magnitude and even the sign of Λ) are only determined by the data fitting itself, in conformal gravity essentially everything is already a priori known. With conformal gravity not needing dark matter to account for galactic rotation curve systematics [14], $\rho_M(t_0)$ can be determined directly from luminous matter alone, with galaxy luminosity counts giving a

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[4]In fact, with the non-relativistic terrestrial and solar system conformal gravity expectations being controlled [13] by a local G whose dynamical generation is totally decoupled [11,12] from that of the cosmological G_{eff}, in conformal gravity cosmology is thus completely freed from the need to be controlled by the Cavendish G.

value for it of order $0.01 \times 3c^2 H_0^2/8\pi G$ or so. Further, with $c\Lambda$ being generated by an energy density lowering particle physics vacuum breaking phase transition in an otherwise scaleless theory, $c\Lambda$ (and thus the $\hbar\lambda S_0^4$ term which simulates it) must unambiguously be negative, with it thus being typically given by $-\sigma T_V^4$ where T_V is a necessarily particle physics sized scale. Then with G_{eff} also being negative, the quantity $\bar{\Omega}_\Lambda(t)$ itself must thus be positive, just as needed to give cosmic acceleration ($q(t) = (n/2 - 1)\bar{\Omega}_M(t) - \bar{\Omega}_\Lambda(t)$). Similarly, the sign of the spatial 3-curvature k is known from theory [11] to be negative, something which has been independently confirmed from a phenomenological study of galactic rotation curves [14]. Moreover, since G_{eff} is negative, the cosmology is singularity free and thus expands from a (negative curvature supported) finite maximum temperature T_{max}, a temperature which is necessarily greater [10,11] (and potentially even much greater [12]) than T_V. And finally, with G_{eff} being negative, the quantity $\bar{\Omega}_M(t)$ must be negative for ordinary $\rho_M(t) > 0$ matter, with $q(t)$ thus being negative in all epochs.[5] Consequently in the conformal theory we never need to fine tune in order to make any particular epoch such as our own be an accelerating one, with repulsive cosmological gravity thus being completely natural to conformal gravity in each and every epoch.

Given only that Λ, k and G_{eff} are in fact all negative in the conformal theory, the evolution of the theory is then completely determined, with the expansion rate parameters being found [10–12] to be given by

$$R^2 = -k(\beta - 1)/2\alpha - k\beta\sinh^2(\alpha^{1/2}ct)/\alpha \quad , \quad T_{max}^2/T^2 = 1 + 2\beta\sinh^2(\alpha^{1/2}ct)/(\beta - 1) \quad , \tag{7}$$

where $\beta = (1 - 16A\lambda/k^2\hbar c)^{1/2} = (1 + T_V^4/T_{max}^4)/(1 - T_V^4/T_{max}^4)$, $\alpha c^2 = -2\lambda S_0^2 = 8\pi G_{eff}\Lambda/3c$. In terms of the parameters T_{max} and T_V we thus obtain

$$\tanh^2(\alpha^{1/2}ct) = (1 - T^2/T_{max}^2)/(T_{max}^2 T^2/T_V^4 + 1) \quad ,$$
$$H(t) = \alpha^{1/2}c(1 - T^2/T_{max}^2)/\tanh(\alpha^{1/2}ct) \quad ,$$
$$\bar{\Omega}_\Lambda(t) = (1 - T^2/T_{max}^2)^{-1}(1 + T^2 T_{max}^2/T_V^4)^{-1}, \quad \bar{\Omega}_M(t) = -(T^4/T_V^4)\bar{\Omega}_\Lambda(t) \tag{8}$$

at any $T(t)$ without any approximation at all. From Eq. (8) we now see that simply because T_{max} is overwhelmingly larger than the current temperature $T(t_0)$, i.e. simply because the universe is as old as it is, it automatically follows, without any fine-tuning at all, that the current era $\bar{\Omega}_\Lambda(t_0)$ has to lie somewhere between zero and one today no matter how big (or small) T_V might actually be, with conformal gravity thus having total control over the contribution of the cosmological constant to cosmic evolution. Conformal gravity thus solves the cosmological constant problem by quenching $\bar{\Omega}_\Lambda(t_0)$ rather than by quenching Λ itself (essentially by having a G_{eff} which is altogether smaller than the standard G), and with it being the quantity $\bar{\Omega}_\Lambda(t_0)$ which is the one which is actually measured in cosmology, it is only its quenching which is actually needed. With conformal gravity thus being able to naturally accommodate a large Λ we are now actually free to allow T_V to be as large as particle physics suggests. Then, for such a large $T_V/T(t_0)$ we see that the quantity $\bar{\Omega}_M(t_0)$

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[5]Included in this class of $q(t) < 0$ universes are the coasting ones in which $q(t) = 0^-$.

has to be completely negligible today[6] so that q_0 must thus, without any fine-tuning at all, necessarily lie between zero and minus one today notwithstanding that T_V is huge. The essence of the conformal gravity approach then is not to change the matter and energy content of the universe at all, but rather only to change their effect on cosmic evolution, with Λ itself no longer needing to be quenched.

In order to fit the Hubble plot data we need to determine the dependence of d_L on z in the conformal theory, something we can readily do now that we have obtained the explicit form of the expansion factor $R(t)$. Thus, for temperatures well below T_{max} and for the naturally achievable [12] $T_V \ll T_{max}$ case of most practical interest to conformal gravity (viz. a case where $T_{max}^2 T^2(t_0)/T_V^4$ can be of order one) we may set

$$R(t) = (-k/\alpha)^{1/2} \sinh(\alpha^{1/2}ct) \quad , \tag{9}$$

so that

$$-q_0 = \tanh^2(\alpha^{1/2}ct_0) = \alpha c^2/H_0^2 \quad , \quad t_0 = \operatorname{arctanh}[(-q_0)^{1/2}]/(-q_0)^{1/2}H_0 \quad . \tag{10}$$

For geodesics $\int_{t_1}^{t_0} cdt/R(t) = \int_0^{r_1} dr/[1 - kr^2]^{1/2}$ we thus obtain

$$(-k)^{1/2}r_1 = \coth(\alpha^{1/2}ct_0)/\sinh(\alpha^{1/2}ct_1) - \coth(\alpha^{1/2}ct_1)/\sinh(\alpha^{1/2}ct_0) \quad . \tag{11}$$

Then, on noting that $\sinh(\alpha^{1/2}ct_1) = (-q_0)^{1/2}/(1+q_0)^{1/2}(1+z)$ where $z = R(t_0)/R(t_1) - 1$ and where q_0 is the current value of $q(t)$, we find that we can express the general luminosity distance $d_L = r_1 R(t_0)(1+z)$ entirely in terms of the current era H_0 and q_0 according to the very compact relation [16]

$$H_0 d_L/c = -(1+z)^2 \left\{ 1 - [1 + q_0 - q_0/(1+z)^2]^{1/2} \right\}/q_0 \quad . \tag{12}$$

Conformal gravity fits to the luminosity distance can thus be parametrized via the one parameter q_0, a parameter which must lie somewhere between zero and minus one, with d_L thus having to lie somewhere between $d_L(q_0 = 0) = cH_0^{-1}(z + z^2/2)$ and $d_L(q_0 = -1) = cH_0^{-1}(z + z^2)$ at temperatures well below T_{max}.

Having obtained Eq. (12) we can now turn to a data analysis. On fitting the same 54 supernovae data points as previously, our best fit is obtained for $q_0 = -0.37$, $M = -19.37$ with $\chi^2 = 58.62$. We display this fit as the upper curve in Fig. (1), and as we thus see, in the detected region the best fits of the standard and conformal models are completely indistinguishable, only in fact departing from each other at the very highest available redshifts. For comparison purposes we find that for $q_0 = 0$ a best fit value of $\chi^2 = 61.49$ is obtained with $M = -19.29$,[7] with fits for other typical values of q_0 being

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[6] $\bar{\Omega}_M(t_0)$ is suppressed by G_{eff} being small, and not by $\rho_M(t_0)$ itself being small, with G_{eff} being made smaller the larger rather than the smaller S_0 gets to be, to thus enable the $c\Lambda/\rho_M(t_0) = \bar{\Omega}_\Lambda(t_0)/\bar{\Omega}_M(t_0)$ ratio to be as large as particle physics suggests while not leading to any 60 order of magnitude conflict with observation.

[7] Such high quality fitting with $q_0 = 0$ has also been noted by other authors [2,15] though not within the context of conformal gravity.

reported in [16].[8] Beyond the purely phenomenological fact that the conformal gravity fits actually provide a good accounting of the supernovae data at all, it is important to stress that as such these fits are the first ones ever obtained in which the cosmological constant is allowed to take a large unquenched particle physics scale value, with the fits thus establishing the empirical fact that it is in fact possible to fit the supernovae data without fine-tuning.

With the standard cosmology requiring deceleration above $z = 1$ and with the conformal cosmology continuing to accelerate, extension of the Hubble plot beyond $z = 1$ will actually enable us to discriminate between the two cosmologies. We thus augment Fig. (2) by adding in the $z > 1$ conformal gravity predictions. The highest curve in Fig. (2) is the conformal gravity prediction for $q_0 = -0.37$, while the middle curve is that for $q_0 = 0$. As we see, these two typical conformal gravity curves start to depart from the standard model expectation fairly rapidly once $z > 1$, with the three curves in Fig. (2) respectively corresponding to apparent magnitudes $m = 27.17$, $m = 27.04$ and $m = 26.75$ at $z = 2$, and to $m = 30.40$, $m = 30.25$ and $m = 29.14$ at $z = 5$. A quite modest extension of the Hubble plot will thus readily enable us to discriminate between standard gravity and its conformal alternative while potentially even being definitive for both.

III. OUTLOOK AND CHALLENGES

While there has yet to be detailed exploration of the $z > 1$ Hubble plot using supernovae standard candles, it is of some interest to note that recently a first $z > 1$ data point was actually established [17], viz. the supernova SN 1997ff which was found to be at a redshift $z = 1.7^{+0.1}_{-0.15}$. To illustrate the data of [17] we have augmented Fig. (2) by adding in the 68% and 95% confidence region values for the measured apparent magnitude m at redshifts $z = 1.65$, $z = 1.7$ and $z = 1.75$. (In the figure the two inner horizontal bars on the vertical data points represent the extent of the 68% confidence region at each of the chosen redshifts while the two outer bars represent the 95% confidence one.) While one should not read too much into a single data point,[9] it is interesting to note that the data can accommodate both the standard and conformal theories, with it being necessary to acquire a whole set of $z > 1$ data points in order to identify any specific trend in the data that there might be, with it as yet being too early to ascertain from available supernovae data whether the $z > 1$ universe is decelerating or accelerating.

Beyond the standard candle supernovae, it has also been noted by Daly [18] that the very powerful FRII bridge radio galaxies can serve as standard yardsticks, and can thus also be used to extract cosmological parameters. As such, this technique serves to complement

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[8]If one also takes the Δz_i errors in the reported redshifts into consideration, the conformal gravity chi squared values for the 54 points get reduced [16] to $\chi^2(q_0 = -0.33) = 54.13$ and $\chi^2(q_0 = 0) = 56.0$, while the standard model chi squared becomes $\chi^2(\Omega_M(t_0) = 0.3, \Omega_\Lambda(t_0) = 0.7) = 53.27$.

[9]Indeed, a shortcoming of these particular data is that SN 1997ff just happens to be gravitationally lensed by two foreground galaxies [17], with its "true" apparent magnitude thus likely to be somewhat larger (viz. dimmer) than indicated in the figure.

the supernovae analyses, and even to potentially go beyond them since radio galaxies are already being seen out to $z = 2$ or so. Interestingly, the data presented in [18] are so far found to be able to accommodate both standard and conformal gravity, with further study of this issue thus having the potential to be quite instructive.

As we noted earlier, that apart from the $z \sim 1$ region Hubble plot, cosmology can also be tested at a variety of much larger redshifts, and it is thus urgent to test conformal gravity at those redshifts as well. While its predictions for the microwave background await the development of a conformal cosmology galaxy fluctuation theory, its initial predictions for nucleosynthesis have already been worked out [19]. What was found was that while the expanding and thus cooling conformal cosmology can readily generate the requisite amounts of primordial helium and lithium, because the cosmology expands altogether slower than the standard cosmology its predictions for deuterium and for ^9Be are substantially different from those of the standard model. Specifically, because of the slowness of the expansion very little primordially generated deuterium manages to survive, but because of this same slowness the cosmology is able to get passed the $A = 8$ nuclear fusion bottleneck (viz. the absence of any stable nuclei with 8 nucleons) and thus primordially produce ^9Be and elements heavier than it, in fact even producing ^9Be with its measured abundance, an abundance 8 orders of magnitude greater than that generatable in the standard theory. Now it was noted in [19] that it would be relatively easy to produce deuterium by spallation once inhomogeneities begin to develop in the universe (i.e. post-primordial but pre-galactic). With an explicit theory for such inhomogeneous deuterium production yet to be developed, conformal gravity thus remains challenged by the deuterium problem just as the standard theory remains challenged by the ^9Be problem. However, since conformal gravity so capably handles the most vexing problem facing the standard theory, viz. the cosmological constant problem, it would thus appear to merit further consideration.

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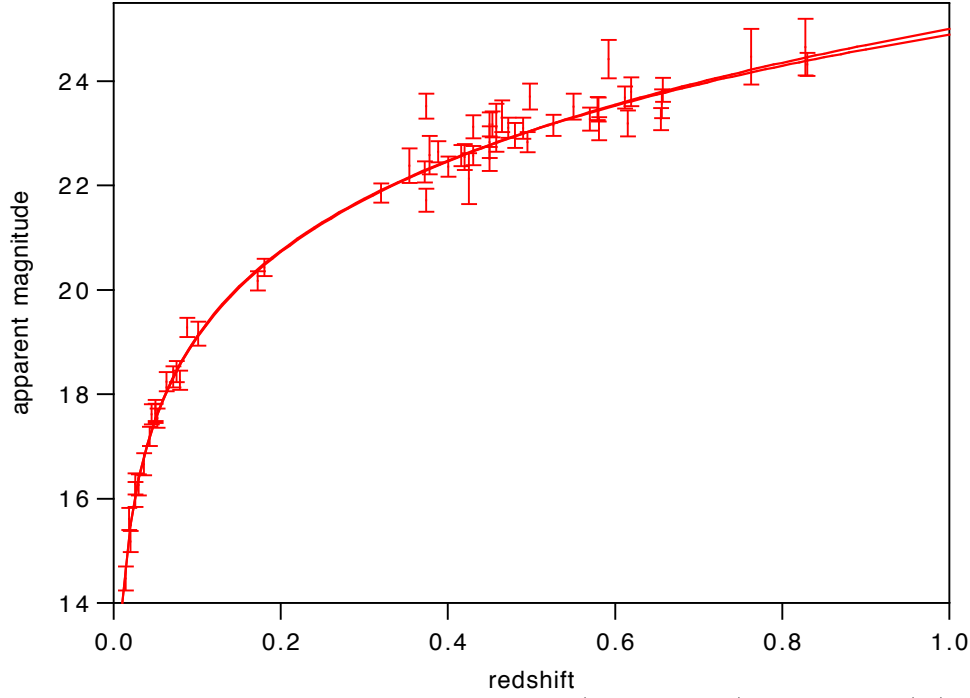
FIG. 1. The $q_0 = -0.37$ conformal gravity fit (upper curve) and the $\Omega_M(t_0) = 0.3$, $\Omega_\Lambda(t_0) = 0.7$ standard model fit (lower curve) to the $z < 1$ supernovae Hubble plot data.
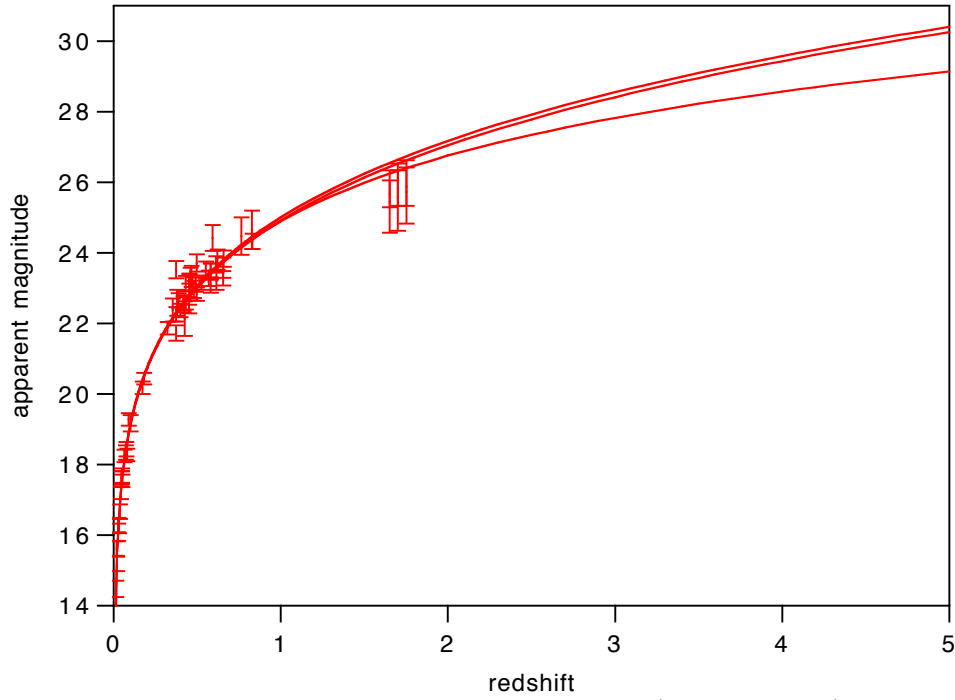

FIG. 2. Hubble plot expectations for $q_0 = -0.37$ (highest curve) and $q_0 = 0$ (middle curve) conformal gravity and for $\Omega_M(t_0) = 0.3$, $\Omega_\Lambda(t_0) = 0.7$ standard gravity (lowest curve).